

# CP violation in scattering of neutrinos on polarized proton target

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## Abstract

In this paper, we analyze the elastic scattering of the muon neutrino beam on the polarized proton target (PPT), and predict how the existence of CP-violating phase between the complex vector  $V$  and axial  $A$  couplings of the left-chirality neutrinos affects the azimuthal dependence of the differential cross section. The neutrinos are assumed to be Dirac fermions with non-zero mass. We show that the azimuthal asymmetry of recoil protons does not depend on the neutrino mass and does not vanish even if  $\beta_{VA} = 0$ . The CP-breaking phase  $\beta_{VA}$  could be detected by measuring the maximal asymmetry of the differential cross section. We also indicate the possibility of using the PPT to distinguish the detector background from the neutrino interactions. Our analysis is model-independent and the results are presented in a limit of infinitesimally small neutrino mass.

*Keywords:* neutrino nucleon scattering, polarized proton target

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## 1. Introduction

Neutrino-nucleon scatterings (NNS) play a crucial role in testing the predictions of the standard model (SM) of electroweak interactions [1, 2, 3]. These reactions are also very important for the neutrino oscillation experiments and understanding the dynamics of the core-collapse supernovae [4]. In addition, the NNS contribute to the energy transfer from the accretion-disk neutrinos to the nucleons [5, 6] and are essential to the terrestrial neutrino

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observation [7, 8, 9]. A measurement of the neutrino-nucleon neutral current elastic scattering cross section allows to search for contribution of the strange sea quarks to the nucleon spin (SciBooNE experiment). The experiments with the NNS can be carried out using the intense, pulsed spallation sources, beta-beams facilities, superbeams and neutrino factories [10, 11, 12, 13]. Various applications of the neutrino beams in area of the NNS and SM tests have been discussed in literature [14, 15, 16, 17, 18].

Although the SM agrees with the experimental data up to available energies, there are numerous theoretical reasons for which it can not be viewed as a ultimate theory. The SM does not clarify why parity is violated in the weak interaction and what is the mechanism behind this violation. The another fundamental problem is impossibility of explaining the observed baryon asymmetry of universe [19] through a single CP-violating phase of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix (CKM) [20]. Presently the CP violation is observed only in the decays of neutral K- and B-mesons [21, 22]. Up to now there is no direct evidence of the CP violation in the leptonic and semileptonic processes. However, the future superbeam and neutrino factory experiments aim at the measurement of the CP-violating effects in the lepton sector, where both neutrino and antineutrino oscillation might be observed. The search of the CP violation in the semileptonic reactions involves mainly the precise measurements of T-odd triple-correlations between the outgoing particles momenta and initial nucleon (nucleus) polarization [23]. All the results are still compatible with the CP conservation scenario.

In such a situation, it is meaningful to look for new tools essential for testing the CP symmetry breaking in the neutral and charged weak interactions. It is necessary to point out that so far no measurements with the (quasi)elastic scattering of neutrino beam on the polarized nucleon (proton, neutron) targets (PNT) have been carried out. One should note that various kinds of the PPT have been used for the nucleon-nucleon elastic scattering and transmission experiments for 15 years, e.g. SATURNE polarized target [24]. The SATURNE Collaboration experience should be used in studies on the future PNT.

In this paper, we focus on the elastic scattering of the muon neutrino beam off the PPT, and consider how the existence of non-zero CP-violating phase between the complex vector  $V$  and axial  $A$  couplings of the left-chirality neutrinos affects the azimuthal dependence of the differential cross section. Next, we show how the recoil proton energy spectrum depends on the initial polarization of proton target.

Our considerations are model-independent and the calculations are made in the limit of infinitesimally small neutrino mass. We use the system of natural units with  $\hbar = c = 1$ , Dirac-Pauli representation of the  $\gamma$ -matrices and the  $(+, -, -, -)$  metric [25].

## 2. Scattering of left-chirality muon neutrinos on polarized protons

We consider the incoming muon neutrino beam, which consists only of the left-chirality and longitudinally polarized neutrinos. We assume that these neutrinos are detected in the standard  $V - A$  neutral current weak interactions with the PPT and both the recoil proton scattering angle  $\theta'_p$  and the azimuthal angle of outgoing proton momentum  $\phi'_p$ , shown in Fig. 1, are measured with a good angular resolution. As our analysis is carried out in the limit of vanishing  $\nu_\mu$  mass, left-chirality  $\nu_\mu$  has negative helicity. We admit the CP violation (equivalent the time reversal violation), so the amplitude includes the complex coupling constants denoted as  $|g_V^L| e^{i\beta_V^L}$ ,  $g_A^L = |g_A^L| e^{i\beta_A^L}$  respectively to the initial neutrino of left-chirality:

$$M_{\nu_\mu p} = \frac{G_F}{\sqrt{2}} \left\{ g_V^L (\bar{u}_{p'} \gamma^\alpha u_p) (\bar{u}_{\nu_\mu'} \gamma_\alpha (1 - \gamma_5) u_{\nu_\mu}) \right. \\ \left. + g_A^L (\bar{u}_{p'} \gamma^5 \gamma^\alpha u_p) (\bar{u}_{\nu_\mu'} \gamma_5 \gamma_\alpha (1 - \gamma_5) u_{\nu_\mu}) \right\}, \quad (1)$$

where  $u_p$  and  $\bar{u}_{p'}$  ( $u_{\nu_\mu}$  and  $\bar{u}_{\nu_\mu'}$ ) are the Dirac bispinors of the initial and final proton (neutrino) respectively.  $G_F = 1.1663788(7) \times 10^{-5} \text{ GeV}^{-2} (0.6ppm)$  (MuLan Collab.) [26] is the Fermi constant. We point out that the induced weak coupling of the left-chirality neutrino ( $g_M^L$ - the weak magnetism) enters additively the  $g_V^L$  coupling, so it is omitted because its presence does not change qualitatively the conclusions concerning the CP violation.

By  $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}$  and  $(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}})\hat{\mathbf{q}}$ , we denote the unit polarization vector and its longitudinal component of the incoming  $\nu_\mu$  in its rest system, respectively. Then  $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$  is the longitudinal polarization of the  $\nu_\mu$ .  $\hat{\mathbf{q}}$  is the incoming muon neutrino LAB momentum unit vector;  $\hat{\mathbf{p}}_{p'}$  is the unit vector of the outgoing proton momentum;  $\hat{\boldsymbol{\eta}}_p$  is the unit 3-vector of the initial proton polarization in its rest frame. The measurement of the azimuthal angle of outgoing proton momentum  $\phi_{p'}$  is only possible when the proton target polarization is known. The  $\phi_{p'}$  is measured with respect to the transverse component of the initial proton polarization  $\boldsymbol{\eta}_p^\perp$ .  $\theta_{p'}$  is the polar angle between the  $\hat{\mathbf{p}}_{p'}$  and the

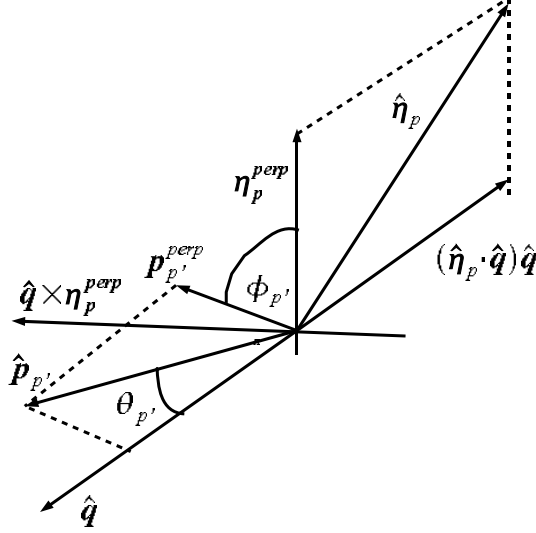


Figure 1: Kinematics and reaction plane for the  $\nu_\mu p$  scattering.

$\hat{\mathbf{q}}$  (recoil proton scattering angle). As it is well known, the vector  $\hat{\boldsymbol{\eta}}_p$  can be expressed, with respect to the  $\hat{\mathbf{q}}$ , as a sum of the longitudinal component of the proton polarization  $(\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}})\hat{\mathbf{q}}$  and transverse component of the proton polarization  $\boldsymbol{\eta}_p^\perp$ , that is defined as  $\boldsymbol{\eta}_p^\perp = \hat{\boldsymbol{\eta}}_p - (\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}})\hat{\mathbf{q}}$ , Fig. 1.

### 3. Azimuthal distribution of recoil protons

The formula for the azimuthal distribution of the scattered protons with  $\hat{\boldsymbol{\eta}}_p \perp \hat{\mathbf{q}}$  is of the form:

$$\begin{aligned} \left( \frac{d^2\sigma}{dyd\phi_{p'}} \right)_{(VA)} &= \frac{E_\nu m_p}{4\pi^2} \frac{G_F^2}{2} (1 - \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \\ &\cdot \left\{ |g_A^L|^2 \left[ -\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{p}}_{p'} \sqrt{\frac{2m_p}{E_\nu}} + y(\sqrt{y^3} - 2\sqrt{y}) + \frac{m_p}{E_\nu} y + (y-2)y + 2 \right] \right. \\ &+ |g_V^L|^2 \left[ y^2 - \hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{p}}_{p'} \sqrt{y^3} \sqrt{\frac{2m_p}{E_\nu}} + y - y\left(\frac{m_p}{E_\nu} + 2\right) + 2 \right] \\ &+ 2Im(g_V^L g_A^{L*}) \hat{\mathbf{q}} \cdot (\hat{\boldsymbol{\eta}}_p \times \hat{\mathbf{p}}_{p'}) \sqrt{y\left(\frac{2m_p}{E_\nu} + y\right)} \end{aligned} \quad (2)$$

$$+ 2Re(g_V^L g_A^{L*}) \left[ \hat{\boldsymbol{\eta}}_{\mathbf{p}} \cdot \hat{\mathbf{p}}_{\mathbf{p}'} (y - 1) \sqrt{y \left( \frac{2m_p}{E_\nu} + y \right) + (2 - y)y} \right] \Big\}.$$

The variable  $y$  is the ratio of the kinetic energy of the recoil proton  $T_p$  to the incoming neutrino energy  $E_\nu$ :

$$y \equiv \frac{T_p}{E_\nu} = \frac{m_p}{E_\nu} \frac{2\cos^2\theta_{p'}}{(1 + \frac{m_p}{E_\nu})^2 - \cos^2\theta_{p'}}. \quad (3)$$

It varies from 0 to  $2/(2 + m_p/E_\nu)$ , where  $m_p$  is the proton mass.

After the simplification of the above formula, Eq. (2), we obtain the new form:

$$\begin{aligned} \left( \frac{d^2\sigma}{dyd\phi_{p'}} \right)_{(VA)} &= \frac{E_\nu m_p G_F^2}{4\pi^2} (1 - \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \left\{ |\boldsymbol{\eta}_{\mathbf{p}}^\perp| \sqrt{\frac{m_p}{E_\nu} y [2 - y(2 + \frac{m_p}{E_\nu})]} \right. \\ &\quad \cdot \left[ \cos(\phi_{p'}) (2|g_V^L||g_A^L|\cos(\beta_{VA})y + (2 - y)|g_A^L|^2 - y|g_V^L|^2) \right. \\ &\quad \left. - 2|g_V^L||g_A^L|\cos(\phi_{p'} + \beta_{VA}) \right] + \left[ (|g_V^L|^2 + |g_A^L|^2) (y^2 - 2y + 2) \right. \\ &\quad \left. + 2|g_V^L||g_A^L|\cos(\beta_{VA})y(2 - y) - \frac{m_p}{E_\nu} y (|g_V^L|^2 - |g_A^L|^2) \right] \Big\}. \quad (4) \end{aligned}$$

It can be noticed that the interference terms between the standard  $g_{V,A}^L$  couplings depend on the value of the relative phase  $\beta_{VA} = \beta_V^L - \beta_A^L$  and are independent of the muon neutrino mass. In the interference part we have angular correlations with the transverse component of the PPT  $\boldsymbol{\eta}_{\mathbf{p}}^\perp$ , both T-odd and T-even. We see that the azimuthal asymmetry of the recoil protons does not vanish even if  $\beta_{VA} = 0$ . The CP-violating phase enters the differential cross section and changes the angle at which the number of the recoil protons will be maximal ( $\phi_{p'}^{max}$ ). For  $\beta_{VA} = \frac{\pi}{2}$  and  $|g_V^L| = 1, |g_A^L| = 1.26$ , this angle is quite large  $\phi_{p'}^{max} \simeq \frac{\pi}{3}$ , see Fig. 2, 3 (solid lines). The azimuthal dependence is illustrated for two assumed values of the muon neutrino energies, i. e.  $E_\nu = 50\text{MeV}$  and  $E_\nu = 1\text{GeV}$ . We calculate the extreme of a function stying at  $|\boldsymbol{\eta}_{\mathbf{p}}^\perp|$  and get  $y_{max} \simeq 0.048$  for  $E_\nu = 50\text{MeV}$ , and  $y_{max} \simeq 0.34$  for  $E_\nu = 1\text{GeV}$ , respectively. In the case of pure axial-vector  $g_A^L$  coupling (short-dashed line) we have different azimuthal dependence of the cross section ( $\phi_{p'}^{max} = 0$ ) than in the case of pure vector  $g_V^L$  coupling (long-dashed line) ( $\phi_{p'}^{max} = \pm\pi$ ). The dotted lines in Fig. 2, 3 show the expected number of scattered protons for the CP-symmetric scenario.

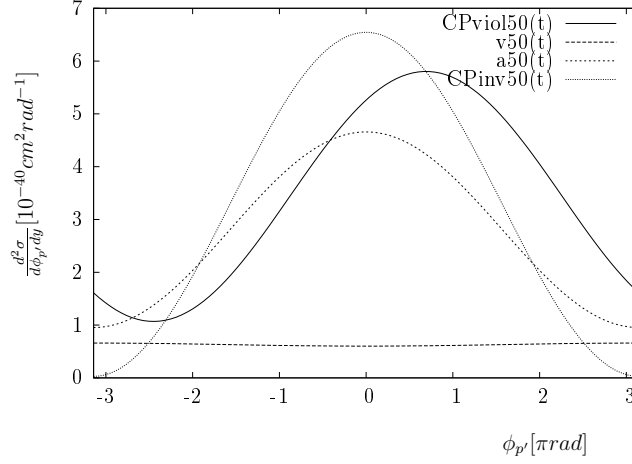


Figure 2: Plot of the  $\frac{d^2\sigma}{dyd\phi_{p'}(VA)}$  as a function of the azimuthal angle  $\phi_{p'}$  for the  $(\nu_\mu p)$  scattering, when  $E_\nu = 50$  MeV,  $y = 0.048$ ,  $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$  and  $|\eta_p^\perp| = 1$ : a) CP violation with  $|g_V^L| = 1, |g_A^L| = 1.26$  and  $\beta_{VA} = \frac{\pi}{2}$  (solid line), b)  $g_A^L = 0, g_V^L = 1$  (long-dashed line),  $g_V^L = 0, g_A^L = -1.26$  (short-dashed line), d) CP conservation with  $|g_V^L| = 1, |g_A^L| = 1.26$  and  $\beta_{VA} = \pi$  (dotted line).

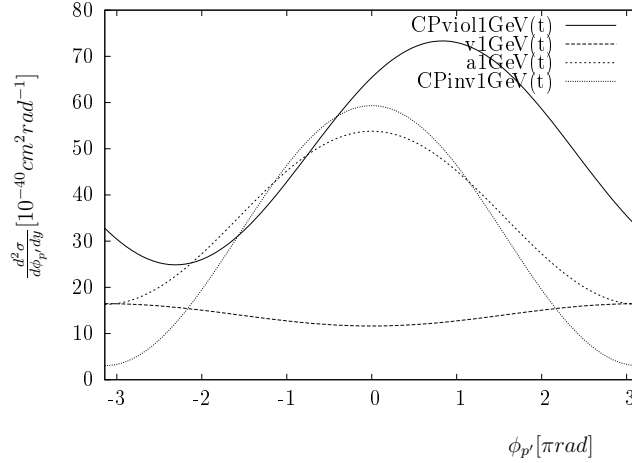


Figure 3: Plot of the  $\frac{d^2\sigma}{dyd\phi_{p'}(VA)}$  as a function of the azimuthal angle  $\phi_{p'}$  for the  $(\nu_\mu p)$  scattering, when  $E_\nu = 1$  GeV,  $y = 0.34$ ,  $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$  and  $|\eta_p^\perp| = 1$ : a) CP violation with  $|g_V^L| = 1, |g_A^L| = 1.26$  and  $\beta_{VA} = \frac{\pi}{2}$ , b)  $g_A^L = 0, g_V^L = 1$  (long-dashed line),  $g_V^L = 0, g_A^L = -1.26$  (short-dashed line), d) CP conservation with  $|g_V^L| = 1, |g_A^L| = 1.26$  and  $\beta_{VA} = \pi$  (dotted line).

#### 4. Spectrum of recoil protons

When the outgoing proton direction is not observed, the formula for the laboratory differential cross section, Eq. 2, has to be integrated over the azimuthal angle  $\phi_{e'}$  of the recoil proton momentum. Finally, one obtains for  $\hat{\boldsymbol{\eta}}_p \not\perp \hat{\mathbf{q}}$ :

$$\begin{aligned} \left(\frac{d\sigma}{dy}\right)_{(V,A)} = & \frac{E_\nu m_p G_F^2}{2\pi} (1 - \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \left\{ |g_V^L + g_A^L|^2 (1 + \hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}}) \right. \\ & + |g_V^L - g_A^L|^2 \left[ 1 - (\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}}) \left( 1 - \frac{m_p}{E_\nu} \frac{y}{(1-y)} \right) \right] (1-y)^2 \\ & \left. - \left[ |g_V^L|^2 - |g_A^L|^2 \right] (1 + \hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}}) \frac{m_p}{E_\nu} y \right\}. \end{aligned} \quad (5)$$

We see that the proton energy spectrum contains only the T-even contributions  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}}$  contrary to the azimuthal recoil proton distribution, where the T-odd correlation occurs. The measurement of the projection of the proton polarization vector parallel to the  $\hat{\mathbf{q}}$  is only possible when the polarization of the proton target is known. For  $E_\nu = 50 \text{ MeV}$  and  $E_\nu = 1 \text{ GeV}$ , we present three interesting cases for  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}} = -1, 0, 1$ , shown in Fig. 4, 5. We assume that the detector energy threshold is  $T_{p'}^{th} = 1 \text{ keV}$ , so  $y \in [0.001, 0.096]$  for  $E_\nu = 50 \text{ MeV}$  and  $y \in [0.001, 0.68]$  for  $E_\nu = 1 \text{ GeV}$ , respectively. It can be noticed that the significant growth of the differential cross section for  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}} = 1$  with  $E_\nu = 50 \text{ MeV}$  (solid line, Fig. 4) is seen for the proton kinetic energy near by the detector threshold. For  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}} = -1$  (long-dashed line, Fig. 4), the number of recoil protons strongly decreases with respect to the unpolarized case  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}} = 0$  (short-dashed line) and is also seen nearly the detector threshold. In the case of the GeV  $\nu_\mu p$  scattering, the increase (and decrease) of the differential cross section for  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}} = 1$  (and for  $\hat{\boldsymbol{\eta}}_p \cdot \hat{\mathbf{q}} = -1$ ) takes place in the whole  $y$  range from the detector threshold to the kinetic maximum, see Fig. 5 with the solid line (and long-dashed line). The dotted lines, shown in the Fig. 4, 5, represent the energy spectrum of protons according to the SM prediction for the unpolarized proton target.

One ought point out that the neutrino beam scattering on the PPT can also be used to distinguish the isotropic background from the proper neutrino interactions, because the incoming left-chirality neutrinos mainly interact with the left-chirality protons. If the initial neutrino beam is scattered off

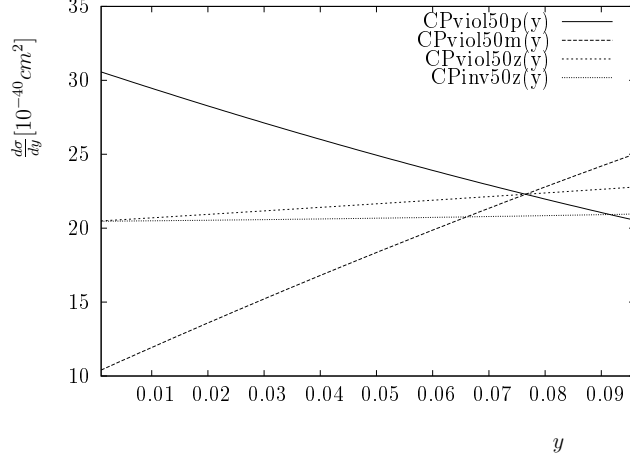


Figure 4: Plot of the  $\frac{d\sigma}{dy}_{(VA)}$  as a function of  $y$  for the  $(\nu_\mu p)$  scattering with  $E_\nu = 50$  MeV and  $\hat{\mathbf{n}}_\nu \cdot \hat{\mathbf{q}} = -1$ : a)  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = 1, |g_A^L| = 1.26, |g_V^L| = 1, \beta_{VA} = \frac{\pi}{2}$  (solid line), b)  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = -1, |g_A^L| = 1.26, |g_V^L| = 1, \beta_{VA} = \frac{\pi}{2}$  (long-dashed line), c)  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = 0, |g_A^L| = 1.26, |g_V^L| = 1, \beta_{VA} = \frac{\pi}{2}$  (short-dashed line), d) SM case with  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = 0, |g_V^L| = 1, |g_A^L| = 1.26, \beta_{VA} = \pi$  (dotted line).

the right-chirality protons, the event number is suppressed, but the detector background stays the same.

## 5. Conclusions

We have shown that the scattering of the left-chirality muon neutrinos on the PPT can be used to measure the CP violation in the neutral current semileptonic weak interaction. Admittance of the complex coupling constants  $g_V^L, g_A^L$  generates the interference terms between the standard  $g_{V,A}^L$  couplings, which are proportional to the  $|\mathbf{n}_p^\perp|$  and dependent on the azimuthal angle of the outgoing proton momentum. The azimuthal asymmetry of the recoil protons is independent of the neutrino mass and does not vanish even if  $\beta_{VA} = 0$ . The CP-breaking phase  $\beta_{VA}$  could be detected by measuring the maximal asymmetry of the differential cross section.

We have also demonstrated that the measurement of the proton energy spectrum in the case of the PPT can be useful in distinguishing the detector background from the neutrino interactions.

To make these tests feasible, the polarized proton target ( $10^{30}$  polarized

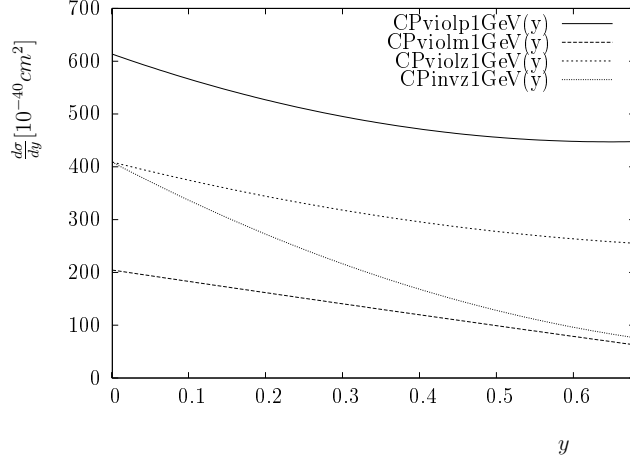


Figure 5: Plot of the  $\frac{d\sigma}{dy(VA)}$  as a function of  $y$  for the  $(\nu_\mu p)$  scattering with  $E_\nu = 1$  GeV and  $\hat{\mathbf{n}}_\nu \cdot \hat{\mathbf{q}} = -1$ : a)  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = 1, |g_A^L| = 1.26, |g_V^L| = 1, \beta_{VA} = \frac{\pi}{2}$  (solid line), b)  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = -1, |g_A^L| = 1.26, |g_V^L| = 1, \beta_{VA} = \frac{\pi}{2}$  (long-dashed line), c)  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = 0, |g_A^L| = 1.26, |g_V^L| = 1, \beta_{VA} = \frac{\pi}{2}$  (short-dashed line), d) SM case with  $\hat{\mathbf{n}}_p \cdot \hat{\mathbf{q}} = 0, |g_V^L| = 1, |g_A^L| = 1.26, \beta_{VA} = \pi$  (dotted line).

protons and more) and intense neutrino beam ( $10^{20}$  neutrinos per year) should be identified. The searching for the CP-violating effects requires the low-threshold, real-time detectors measuring both the polar angle and azimuthal angle of the outgoing proton momentum with a high resolution. It is worthwhile mentioning the proton and neutron polarized targets for nucleon-nucleon experiments at SATURNE II [24]. New low-threshold technology is being developed, e. g. the silicon cryogenic detectors and the high purity germanium detectors [27].

The experiments using the PPT in the neutrino-nucleon scattering will be a real challenge for experimental groups, but they could detect the existence of the CP-violating phases and non-standard neutral and charged current weak interactions. In a separate paper, we will search for the exotic effects beyond the SM in the neutrino beam scattering off the polarized nucleon target.

## References

- [1] S. L. Glashow, Nucl. Phys. **22** (1961) 579.
- [2] S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264.

- [3] A. Salam, in Elementary Particle Theory, (Almquist and Wiksells, Stockholm, 1969).
- [4] A. B. Balantekin and G. M. Fuller, J. Phys. G **29** (2003) 2513.
- [5] M. Raffert, H. T. Janka, K. Takahashi and G. Schafer, Astron. Astrophys. **319** (1999) 122.
- [6] J. P. Kneller, G. C. McLaughlin and R. Surman, J. Phys. G: Nucl. Part. Phys. **32** (2006) 443.
- [7] P. Vogel and J. F. Beacom, Phys. Rev. D **60** (1999) 053003.
- [8] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D **66** (2002) 033001.
- [9] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, hep-ph/0603078
- [10] F. T. Avignone and Y. V. Efremenko, J. Phys. G. **29** (2003) 2615.
- [11] K. Scholberg, Phys. Rev. D **66** (2002).
- [12] C. Volpe J. Phys. G **30** (2004) L1.
- [13] S. Geer, Phys. Rev. D **57** (1998) 6989; Phys. Rev. D **59** (1999) 039903.
- [14] J. Serreau and C. Volpe, Phys. Rev. C **70** (2004) 055502.
- [15] G. C. McLaughlin, Phys. Rev. C **73** (2006) 033005.
- [16] C. Volpe J. Phys. G **31** (2005) 903.
- [17] G. C. McLaughlin and C. Volpe, Phys. Lett. B **591** 2004 (229).
- [18] A. B. Balantekin, J. H. de Jesus and C. Volpe, Phys. Lett. B **634** (2006) 180.
- [19] A. Riotto and M. Trodden, Annu. Rev. Nucl. Part. Sci. **49** (1999) 35.
- [20] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
- [21] J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Lett. **13** (1964) 138; B. Aubert et al., Phys. Rev. Lett. **87** (2001) 091801; K. Abe et al., Phys. Rev. Lett. **87** (2001) 091802.

- [22] CPLEAR Collaboration, A. Angelopoulos et al., Phys. Lett. B 444 (1998) 43.
- [23] L. J. Lising et al., Phys. Rev. C **62** (2000) 055501.
- [24] J. Ball et al., Nucl. Instr. and Meth. in Phys. Res. **A** 381 (1996) 4.
- [25] W. Greiner, B. Muller, Gauge Theory of Weak Interactions, Springer, 2000.
- [26] D. M. Webber et al., Phys. Rev. Lett. **106** (2011) 041803.
- [27] B.S. Neganov et al., hep-ex/0105083.